Report on the Workshop on the Scientific Exploration of Simulation Phenomena

S.Y. Harmon
Zetetix, Oak Park, CA
harmon@zetetix.com

ABSTRACT

The Army Model and Simulation Office and the Defense Modeling and Simulation Office sponsored a workshop on scientifically exploring simulation phenomena in the late Spring of 2002. These sponsors invited 16 leaders in modeling and simulation from academia, industry and the U.S. Government to participate. They asked these participants to

- Determine if fundamental knowledge of the nature of simulation could exist,
- Assess whether a scientific approach to the study of simulation could improve that knowledge, and
- Recommend further steps (including performing research) to improve our knowledge of simulation fundamentals and, through that knowledge, improve current simulation workforce quality as a whole.

In the course of this workshop, the participants explored the issues of simulation as a science, the nature of simulation fundamentals, past applicable work, the means to improve workforce quality, and the means to improve our knowledge of simulation fundamentals. By the workshop's end, they had successfully created initial preliminary lists of the knowledge fundamental to simulation and of fundamental research recommendations. They could not, however, agree on whether a science of simulation exists or even should exist to improve our knowledge of simulation fundamentals. They also created a list of short-term actions through which to begin improving the knowledge of fundamentals that simulation practitioners possess.

INTRODUCTION

On 4-6 June 2002, the Army Model and Simulation Office (AMSO) and the Defense Modeling and Simulation Office (DMSO) sponsored the Workshop on the Scientific Exploration of Simulation Phenomena at the National Defense University in Washington, DC. They invited 16 leaders in modeling and simulation from academia, industry and the U.S. Government to participate (see Table 1). The sponsors asked these participants to

- Determine if fundamental knowledge of the nature of simulation could exist,
- Assess whether a scientific approach to the study of simulation could improve that knowledge, and
- Recommend further steps (including performing research) to improve our knowledge of simulation fundamentals and, through that knowledge, improve current simulation workforce quality as a whole.

Table 1. Workshop Participants and their Affiliations.

Participant	Affiliation
Mr. Lawrence Alexander	Science Applications International Corp./Defense Modeling and Simulation Office
Mr. Bruce Bailey	Science Applications International Corp./Defense Modeling and Simulation Office
Dr. Paul Davis	The Rand Corp.
Mr. David Gross	The Boeing Company
Mr. Scott Harmon	Zetetix
Mr. Dell Lunceford	Army Model and Simulation Office
Prof. David Nicol	Dartmouth College
Dr. Susan Numrich	Defense Modeling and Simulation Office
Dr. Dale Pace	Johns Hopkins University, Applied Physics Laboratory
Dr. Ernest Page	Abstraction and Associates/Army Modeling and Simulation Office
Dr. Marc Raibert	Boston Dynamics, Inc.
Dr. Randall Shumaker	University of Central Florida, Institute for Simulation and Training
Prof. William Swartout	University of Souther California, Institute for Creative Technologies
Mr. William Waite	The AEgis Technologies Group, Inc.
Dr. William Whelan	Concepts and Technology Group
Prof. Bernard Zeigler	University of Arizona, Tucson

While simulation has contributed substantially to science, the understanding of its basic nature has come largely from application experience and limited engineering studies. Relatively few have applied rigorous scientific discipline to characterize and understand the phenomena associated with simulation. Without a serious scientific approach to answering the predominant questions plaguing the advancement of simulation, it will remain an art with only a few tenets to guide its practitioners. This workshop was supposed to have created a single but crucial stepping stone from which the journey to scientifically characterizing the fundamental nature of simulation can begin.

The workshop began with presentations from the participants that summarized their individual positions on the workshop topic. Working sessions constituted the bulk of the workshop in which the participants considered past scientific work on simulation, simulation observables and phenomena, hypotheses about simulation behavior, and possible experiments to improve our knowledge of simulation fundamentals. This paper summarizes the results from these working sessions and the recommendations proposed by the participants. The workshop record provides a detailed account of its proceedings [1].

SIMULATION AS SCIENCE

The participants all came to this workshop with diverse opinions of science, simulation and their possible relationships. In the working sessions they examined the attributes of science, discussed the limits of technology imposed by a lack of science, and explored the dependencies between science and engineering. The participants spent considerable time debating the possible relationships between science and simulation technology. Despite this significant discussion, they could not agree that a scientific approach to understanding the phenomenology underlying simulation would provide any substantial benefits over other less disciplined approaches. Their positions broke roughly into four, nonexclusive, arguments:

- Simulation is technology but not science (although, perhaps, an important tool of science). Applying the scientific method to understanding simulation may yield interesting but not necessarily useful results for the time being.
- Simulation consists of observable phenomena that the application of the scientific method can explain. The resulting explanations can provide the fundamental knowledge needed to advance simulation technology. Scientific study of simulation will certainly produce the core knowledge necessary to advance it as an engineering discipline.
- Simulation is a technology too underdeveloped to sustain the productive application of rigorous scientific method. It needs many more casual exploratory observations from which scientific knowledge may later evolve.
- Simulation is better considered as an engineering discipline. Taking an engineering approach to its study will produce more immediately useful results than trying to explain it scientifically.

Most of the participants felt strongly about their positions on this particular issue so no reconciliation seemed likely within the workshop's timeframe.

SIMULATION FUNDAMENTALS

Despite their lack of agreement on the relationships between simulation and science, the participants concurred unanimously that knowledge of the fundamental nature of simulation could exist and that that knowledge would play an important role in substantially improving simulation workforce quality. They also believe simulation as an inherently multi-disciplinary field that draws parts of its fundamentals from mathematics, science and engineering and that the mix of contributing disciplines differs as the simulands change. They recognized that building a simulation requires three skill sets:

- Those inherent and unique to simulation,
- Those associated with developing complex information systems (e.g., computers and software), and
- Those associated with the domain that the simulation represents.

The participants did not agree that we actually possess this knowledge of simulation fundamentals. However, over the course of several sessions, they did enumerate many components of the knowledge unique to simulation. A set of processes in the simulation development chain best describes these components:

- **Describing simulation representational characteristics** (i.e., knowledge of all of the elements of model and simulation fidelity and the relationships between a simulation and its simuland);
- **Mapping user needs into specific simulation capabilities** (i.e., knowledge necessary to extract simulation objectives from users and formulate those objectives into required simulation capabilities);

- **Abstracting models from referent information** (i.e., knowledge of mathematical abstraction and modeling from both data and models of the simulands of interest, including representing time and events);
- **Designing and building simulations from models** (i.e., knowledge needed to choose algorithms or models to meet user needs, designing new simulation components or selecting existing components to represent those algorithms, and assembling those components and simulation infrastructures, including simulation engines, into working simulations; this requires knowledge of such factors as simulation complexity, performance, interoperability, observability, controllability and comprehensibility);
- **Interfacing the simulation with people and other systems** (i.e., knowledge about connecting simulations to people and other parts of the environment in which they must perform; this requires knowledge of such factors as immersion, interactivity, man-simulation interfaces and connectability);
- **Determining if a simulation can meet user needs** (i.e., knowledge about simulation validation and verification including representational requirements tracking, conceptual model validation, intermediate product verification, simulation testing and results validation); and
- **Preparing and using simulation to achieve user objectives** (i.e., knowledge about constructing and implementing simulation scenarios, simulation setup, controlling simulation execution and analyzing simulation results).

The participants also believe that simulationists need the knowledge to handle the problems associated with constructing and operating any complex information system including aspects of software engineering, system engineering and program management. They enumerated several details of these disciplines but agreed that this knowledge did not distinguish simulation from any other large information system. Thus, while necessary to simulation it does not form the core of the knowledge fundamental and unique to simulation.

The participants also elucidated three of several potential uses for the knowledge of simulation fundamentals:

- Helping to unearth the principles that underlie simulation,
- Forming a basis for academic programs in simulation, and
- Defining an expected set of practices and skills that simulationists need to perform well in their jobs.

The length and scope of the workshop prevented its participants from developing these lists exhaustively but these lists represent a reasonable sampling of simulation fundamentals and their uses.

PAST APPLICABLE WORK

In their considerations of past work applicable to simulation science, the workshop participants identified either the existence of prior work or the lack of it in some cases.

They listed several areas of simulation in which researchers have performed rigorous and fruitful scientific work:

- Time flow management,
- Event list management,
- Monte Carlo representation convergence,
- Random number generators,
- Representation and performance,
- Analyzability and expressiveness,
- Performance and expressiveness,
- Heuristics,
- Simulating perceived phenomena,
- Representing human behavior phenomena, and
- Simulation programming and implementation.

The workshop's final report contains an extensive bibliography that cites examples of much of this prior work [1].

Despite the existence of this considerable prior work, some participants expressed concern with the state of research in simulation in general. They noted that much of the current simulation literature consists of observations rather than reports of the results of rigorously controlled experiments. Much of the controlled experimentation that researchers have performed does not follow established experimental protocols and few simulation researchers report their experiments in sufficient detail to permit their replication. These deficiencies prevent the simulation community from confidently determining what approaches work, why they work and what could be done to improve them. As a result, little of the theory underlying simulation has been rigorously validated. In fact, some of the participants believe that some of this theory cannot be validated through either controlled experiments or systematic observations. This deficiency also prevents comparing the merits of one theory against another, competing, one. Some feel that the current simulation culture may not even support the data collection efforts and controlled experiments needed to gain a scientific understanding of simulation. However, the participants did identify several sources of data from which to develop and validate simulation theory [2-5]. These sources simply represent examples of the possible resources and are not endorsed by the participants necessarily.

IMPROVING SIMULATION WORKFORCE QUALITY

The workshop participants carefully examined the factors that contribute to workforce quality. These factors form two groups:

- Improving the simulation profession, and
- Improving simulation education.

The factors in these groups are coupled and the participants discussed these coupling modes to a limited extent.

Improving the Simulation Profession

The participants explored the need for defining simulation as a distinct specialty as opposed to leaving it as a general tool for many other disciplines. Most believe that simulation can and should exist as a separate profession. Evolving simulation as a profession will better develop the simulation industry and that will make more resources, and therefore choices, available to simulation customers. Further, simulation projects demand people with a comprehensive knowledge of simulation. Employers want a simulation professional who can address a wide range of problems and that requires identity, integrity and persistence in the profession. So, not only must simulation professionals believe that they can get a job but they must also have pride in their profession.

The workshop participants distinguished several contributions to professionalism:

- Practitioner certification and licensing programs,
- Professional standards and best practices,
- Customers concerned with and willing to pay for quality work, and
- Employing organizations that maintain professional standards.

Several of the participants were familiar with the ongoing effort to develop a simulation professional certification and they felt that it could also contribute to identifying simulation fundamentals [6]. Most of the participants agreed that a meaningful professional certification (e.g., as strong as that of professional engineers) could serve the simulation profession well.

The workshop participants saw capturing current best practices as important. These practices should represent the skills, procedures and practices that experienced simulation practitioners employ when executing their craft. AMSO is currently cooperating with DMSO to define a set of best practices. They will first put something together for the short term then build upon the product of that initial effort through a peer-reviewed process to improve its quality. In addition, some of the workshop participants are working to create a set of monographs that capture the breadth of simulation practices. These volumes will represent the body of knowledge that simulationists should have and describe the practices and processes that simulationists should competently execute.

All of the workshop participants believe that the existence of a well-defined simulation profession will improve the quality of simulation products. However, they recognize that a customer base must exist to pay for, even demand, the quality work that a simulation profession will produce. Many of the participants strongly feel that if a simulation profession exists and if simulationists have pride in that profession then a market will exist to hire those people. We must also create a marketplace where customers emphasize their expectations of quality workmanship in the simulation products and services they buy.

Improving Simulation Education

The participants explored several avenues for educating simulationists:

- **Journeymanship –** Historically, immature fields developed and propagated their core knowledge through apprentice-journeyman relationships. These relationships continue to thrive, even in well-established technical areas, in industry (e.g., The Boeing Company). Also, one can see graduate school as a form of apprenticeship. Employers hiring at the journeyman to master level should expect individuals to execute a set of practices in ways indicative of good workmanship.
- **Simulation shortcourses** - Some participants feel that shortcourses and on-the-job-training provide an important means by which to educate simulation practitioners over the short term (i.e., ≤ five years). However, shortcourses suffer from two problems. They give the students knowledge but no hands-on experience and they need people with broad experience to teach them.
- **Non-degreed simulation courses** - The university system could create a package of courses focused upon simulation technology. The potential consumers of theses courses fall into two groups: simulationists and people who must understand simulation (e.g., program managers). Current simulation program managers typically understand software development and program management but not specifically simulation. Survey courses guide people toward taking the proper coursework and help them choose an appropriate simulation specialization if they want to move into a degree program.
- **Advanced degree programs in simulation –** Some participants believe that the apprenticeship model that present MS and PhD programs support, some already established, supply another short-term source of educated simulationists. Several universities have already started masters and doctoral programs in simulation [7-9].
- **Basic degree program in simulation** - Currently, no college or university in the USA offers an undergraduate degree in simulation. The participants debated the soundness of establishing such a program and could not come to agreement on this issue. Others have also considered this education option [10-12]. Some participants feel that we want to have such programs in the five to ten year timeframe. Others feel that advanced degree programs are sufficient to serve the profession. This group expressed some concern about replacing important existing courses with those required for a simulation major. Those in favor of an undergraduate program in simulation believe that sufficient information exists to fill a basic curriculum and that the profession needs this level of simulation education. However, significant difficulties may hamper schools trying to create a formal simulation specialty in existing core disciplines because their current core curricula are already packed with present material. The participants in favor of an undergraduate simulation degree further believe that a simulation curriculum will give students modern skills that they cannot now get in any orderly manner. The participants finally agreed that if such a program existed then it must be broad enough so as not to unnecessarily limit the students'

employment options. They also agreed that the success of a simulation degree depends upon the demand for the people who earn that degree. However, most of the participants feel that such a job market does exist.

IMPROVING KNOWLEDGE OF SIMULATION FUNDAMENTALS

The participants spent considerable time assessing the current state of simulation knowledge (in particular, the fundamentals of simulation) and identifying potentially fruitful ways to improve this situation. These ways consist of improving the quality of the knowledge record and adding to the current body of knowledge.

Improving Knowledge Quality

The participants recognized that the existing literature recording modeling and simulation knowledge is both broad and rich and supported by an assortment of textbooks, journals, workshop and conference proceedings, and other sources [1]. This knowledge roughly separates into two disjoint classes:

- Results of scientifically rigorous studies of narrow areas (e.g., random number generators, event list management, simulation algorithm analysis), and
- Descriptions of approaches to solving both general and specific simulation problems, some loosely tested and others untested.

The participants all concurred that we must understand the limits of this existing knowledge base, regardless of its quality, before proposing additional efforts to amass yet more knowledge (e.g., research).

The workshop participants also agreed unanimously that past simulation projects represent an untapped resource of lessons learned that the core body of simulation knowledge must incorporate. Unfortunately, most of these past efforts have not documented their lessons learned and present efforts have not improved that practice. Further, few programs typically perform any analysis or assessment to determine their failure modes and how they might be avoided.

The participants recommended two primary, and coupled, ways to improve the literature base:

- Improve the volume of the archival literature documenting lessons learned, and
- Improve the quality of individual publications through consistent peer review.

In general, the simulation field lacks a significant archival literature base for lessons learned. We must change this trend to improve the documentation associated with large simulation projects. Any improvements must include documentation of both failed and successful efforts.

The peer review process can improve the quality of published work in a field and many professional organizations rely upon peer review for their publications. Stricter and more widespread peer review processes for simulation publications can push simulation people back into quality publications and that can help people new to the workforce separate good work from bad.

Adding to Current Knowledge

Adding to our current knowledge of simulation fundamentals supplies another way to improve our knowledge base. The workshop participants both discussed the general means to add to current knowledge and proposed potentially fruitful directions for fundamental research that would produce that knowledge.

The participants largely agreed that today's simulation literature is rich in theory and poor in actual high quality data against which to validate that theory and extend it where necessary. From a scientific perspective, the community needs more visible data through which to discern the fundamental nature of simulation and this data is not now available. This lack of available data dramatically hinders the growth of any simulation science. Many reasons exist for the absence of observations of simulation phenomena in the public domain but, despite these, the situation must be remedied.

This data can come from three possible sources:

- Mining existing references for data,
- Passively observing simulation development and use, and
- Performing controlled experiments.

Each of these sources has its advantages and disadvantages. Mining existing references involves combing the technical literature for observations, data from controlled experiments and lessons learned for data depicting simulation phenomena. This source provides the cheapest but, perhaps, least reliable data since the quality of that data may not be well characterized. Structured observations may suit today's climate by enabling data collection from ongoing efforts on a non-interference basis. This approach can lead to a succession of improvements to current practices. However, capitalizing on existing programs limits the kinds of issues that one can explore without performing controlled experiments. Controlled experiments may require the greatest investment but will also provide the best data and can address specific questions of interest. Clearly, a combination of these techniques should remedy the present lack of quality data. For instance, exploring data from mining or observation may produce questions that controlled experiments can economically answer. In fact, we may have a unique opportunity here because no one else is presently looking at the experiments that would advance the simulation technology.

Characterizing error is critical to collecting data from any of these sources. This involves both

- Determining the possible sources of errors and
- Assessing, quantitatively whenever possible, the influence of those error sources.

Simulation researchers have historically not addressed the influences of error upon their observations very well. Only recently have a small group of simulation researchers begun to explore the effects of uncertainty on their simulation results [13, 14]. This conscientiousness represents a good beginning that should become pervasive in all future efforts to gather data on the fundamental nature of simulation.

The workshop sessions were organized to lead the participants to think about simulation from a scientific perspective. The three middle sessions asked the participants to identify observable phenomena of simulation, possible hypotheses about simulation and experiments that might improve our knowledge of simulation. The participants all enthusiastically contributed to this exercise but the ultimate outcome from these three sessions was quite different than one might expect. This thinking defined a research agenda of questions fundamental to simulation. Exploring this research agenda will assuredly add to our current knowledge of simulation fundamentals.

The participants identified several important areas of fundamental simulation research:

- **Factors contributing to making simulations too hard** – This research direction will explore those factors that make simulations too hard to develop and use. The participants identified two primary factors that contribute to this: (1) a lack of adequate knowledge about the phenomena being modeled (i.e., ignorance) and (2) the complexity of the relationships and the number of parameters and interactions involved (i.e., complexity). However, beyond these general observations we understand little about the relationships between users' objectives, simuland complexity, simulation complexity and actual use patterns. Knowledge of this sort could help people successfully and economically achieve the objectives of large scale simulation efforts.
- **Criteria for choosing specific over general simulation approaches** - This research will explore the issues associated with choosing to develop and use either specific narrowly scoped simulations or composable simulations built upon general simulation infrastructures. The participants understand that some problems lend themselves best to simulations developed particularly for a narrow use while others require more general approaches. Building simulations specific for a special problem can be fast and cheap while building general simulation infrastructures increases their flexibility and broadens the number of problems they can explore. But, we neither clearly understand which problems best yield to these different implementation philosophies nor do we understand the underlying reasons for that. This work could help to identify those situations when determining if the complications of reusability and interoperability are necessary and, thus, worth their added cost and technical challenge.
- **Dealing with limited referents** – The participants recognize that in some important situations the ability to collect copious data on a simuland is impossible or impractical (e.g., missile flights). This recognition suggests the need for research into building referents from limited data and using those referents properly. This direction will explore the areas of experiment design, data collection and analysis, and small sample statistics to optimize experimentation effort and to define the confidence limits associated with using referents constructed from small sample sizes. It may also identify the information that one must associate with referents to support their sensible employment. Further, this direction will determine how these referents can best be used in both effective model abstraction and meaningful validation.

- **Relationships between simulation fidelity and interoperability with other components** – Some participants recommended fundamental research into the connections between fidelity and interoperability. This direction suggests that constraints may exist on the interoperability between simulations with different representational capabilities (i.e., fidelity). It also covers the problem of interacting simulations sharing consistent interpretations of shared data. Knowing these relationships will help build simulation compositions from reusable components.
- **Inherent limitations of simulations of complex adaptive systems** – Some participants proposed that simulations of complex adaptive systems (e.g., systems that adapt to changes in their environments such as humans or robots) differed substantially and fundamentally from simulations of physical systems. They thus recommended research into how these differences constrained the utility (including prediction limits) of this type of simulation. This research will help to define the inherent limits on the accuracy of complex adaptive system simulations. Such fundamental knowledge can help managers and users alike determine the extent of their investments and reliance upon simulations of these systems.
- **Applications and limitations of visualization techniques** - The simulation community currently employs visualization widely for a variety of simulation purposes (e.g., output analysis, process control) without adequately understanding its fundamentals. The participants know of no literature describing the applications and limitations of visualization. That represents a critical area requiring better understanding that we could obtain through fundamental research.
- **Effectiveness of abstraction techniques to achieve a particular purpose** - The process of analyzing a problem to determine the simulation representations needed to solve that problem (i.e., abstraction for a purpose) represents a fruitful fundamental area of exploration. This research will examine the effectiveness of various abstraction techniques as they are applied to a variety of purposes. Abstraction processes are fundamental to modeling and simulation yet we still understand their effectiveness in various situations poorly. Research in this area will advance our understanding of the fundamentals of abstraction through both systematic observations and controlled experiments.
- **Dependencies between simulation representation and implementation** – The workshop participants feel that we presently do not sufficiently understand the nature of the dependencies between a simulation's content, its models and the infrastructure through which it is implemented. These aspects are not independent although people do sometimes treat them that way. Research to characterize these dependencies will improve simulation design and reduce implementation risk. It will also advance the opportunities for reuse by shedding light onto the effects of implementation decisions on component and infrastructure interoperability. This research can involve controlled experiments to determine the effects of different implementation environments on simulation fidelity. The participants identified several implementation-related factors that

research could enlighten. These factors all involve selecting the best operational or implementation characteristics for a simulation including

- Architectural design,
- Implementation approaches for different models (e.g., object-oriented design),
- Implementation approaches to achieve particular purposes,
- Implementation languages, and
- Computational styles.

No information currently exists beyond people's direct experiences and prejudices in making these (and other) implementation-related decisions. In some cases, our fundamental knowledge of the factors affecting these decisions is pathetic and thus the resulting decisions are slipshod. Therefore, these are crucial areas where we need to make progress.

- **Specifying simulation conceptual models** - The problem of specifying simulation conceptual models has not been satisfactorily solved yet. The solution to this problem can help to regularize the practice and processes associated with simulation. Further, a quality explicit conceptual model can reduce simulation development and reuse cost.
- **Building comprehensible simulations** - The workshop participants agreed on the importance of the relationships between a simulation's representation and its comprehensibility (i.e., the ability to understand its representations and their limitations). Comprehensibility is a crucial factor in simulation reuse. Having complete information associated with a model will also have a significant effect upon the scientific utility of the end product from that model. Some participants believe that we may need to build comprehensible simulations differently than the simulations of today in that we may need to explicitly represent our design decisions in the simulation product. People currently do not know much about comprehensibility. Thus, the participants recommended systematic research, possibly involving controlled experiments, into this area.

The list of fundamental research topics represents, by no means, an exhaustive enumeration nor has it been prioritized in any way. However, this list came from the synthesization of many hours of discussion in the workshop and, as a whole, provides the collected thoughts of some of the finest and most careful thinkers in the modeling and simulation field.

SHORT TERM ACTIONS

In the last session, the participants recommended several near-term (i.e., within 1-2 years) actions that could improve the fundamental knowledge of simulation throughout the workforce. These recommendations encompass both building that fundamental knowledge and distributing it within the community:

- **Conduct lessons learned workshops** – The participants recommended conducting at least one workshop on the lessons learned from large simulation projects. They felt that the Millennium Challenge 2002 exercise [15] provides the most immediate and valuable opportunity. This workshop should solicit papers recounting the means by which simulation practitioners actually solved their problems (e.g., allocating multi-cast groups). These papers would undergo a peer-review process to improve the quality of the workshop proceedings. Incentives could be given to encourage publishing both positive and negative experiences. If the first workshop proves successful then, perhaps, this could develop into a regular series. This workshop series would supply a set of real world observations from which we could abstract the fundamentals of simulation. The participants suggested several possible topics that this workshop could cover (e.g., conceptual models, system design, system integration, multi-cast groups, tools).

- **Conduct a simulation competition** – The participants suggested running a simulation competition in another attempt to create and collect data on simulation phenomena [16]. This competition will ask graduate students studying simulation to solve some specific simulation problem (e.g., create a conceptual model of a simulation of the Chunnel, build a simulation of some observable phenomena). The competitors may be asked to devise measures of merit of their simulation as well. The submissions to this competition will then create a large body of observations that one can study to lead to stronger hypotheses about the simulation phenomena involved that can then be tested more rigorously. The workshop participants also discussed several incentives through which to encourage broad participation (e.g., monetary prizes, recognition, subsidized travel to an awards ceremony).
- **Compile a glossary of simulation terms** – The participants unanimously agreed on the need for a glossary of simulation terms that captures and unifies current usage of simulation terminology. They believe that the consistency of the lexicon reflects the maturity of the field. Some participants recommended developing this glossary through a peer review process. Others noted that several simulation glossaries currently exist and recommended that they serve as resources [17]. Most participants also agreed that this glossary should serve simulation communities broader than just the DoD in order to ensure consistency of the resulting lexicon.
- **Construct a taxonomy of existing simulation literature** – The participants recognized the existence of a vast literature base supporting simulation. However, this literature tends to be disjoint, uncorrelated and of wildly varying quality in places. As a result, some of the participants believe that building a topical taxonomy of simulation and overlaying that taxonomy with the coverage of the existing literature would be hugely useful to the community. This annotated taxonomy can help us better understand the limits of the existing modeling and simulation knowledge. Some researchers have already created initial versions of such a taxonomy [18, 19]. The results of these efforts need to be integrated into a consistent view but they provide a starting point for this work.
- **Formulate a recommended reading list for modeling and simulation** – Most of the participants believe that a need exists for a recommended reading list on

modeling and simulation. This list will identify the most important literature (e.g., texts, technical papers) with which simulationists should maintain familiarity. Such a list can also take the first step in accumulating a common body of modeling and simulation knowledge. It can also help focus those interested in learning about different aspects of simulation. The participants agreed that annotating the entries of this list is essential to establishing its pedigree and to guiding people to its proper use. The participants recommended assembling and publishing such a list on an accessible public website.

- **Consider instituting a reviews of modeling and simulation journal** – Some of the participants suggested establishing a refereed journal that published high quality opinionated survey articles on modeling and simulation. This journal will parallel the intent behind the Reviews of Modern Physics [20]. Currently no journal fills this void in the simulation literature.
- **Compile and publish a modeling and simulation monograph series** – Some of the participants proposed developing a series of monographs that captured the fundamental knowledge and best practices of modeling and simulation. They recommended that this series document the knowledge that a journeyman needs to be proficient in modeling and simulation. Each book will contain a survey and a threaded tutorial of its topic. This series will consist of six to ten volumes and each volume will address topics large enough to serve as the text for an undergraduate course on the topic. It can be packaged as a CD, as well as a printed form, to increase its accessibility. This series will capture the current knowledge and give those concerned with improving the workforce something upon which to build. It will also supply the academic community the material upon which to build modeling and simulation coursework. Regarding this recommendation, the participants could not agree on the best way to proceed. Some suggested inviting contributing authors to a workshop, peer-reviewing their articles and building the series incrementally from those. Others proposed having the entire series written within one year was a better approach. Some participants thought that we should identify where deficiencies in the existing literature exist then enlist authors to address those areas while others felt strongly that they already knew the topics for this series. However, all of the participants agreed that such a series should leverage the breadth of the existing simulation literature base.

The first two of these recommendations address the lack of data that hampers the scientific exploration of simulation phenomena. The next three structure existing information on simulation to make it more accessible to practitioners. The last two recommendations create new knowledge resources for simulationists.

SUMMARY AND CONCLUSIONS

The workshop participants successfully created initial and preliminary lists of the knowledge fundamental to simulation and of fundamental research recommendations. They could not, however, agree on whether a science of simulation exists or even should exist. In the end, that failing may be of little consequence to the workshop's sponsors.

The workshop participants also recommended a set of short-term actions to advance and disseminate our fundamental knowledge of simulation. These actions address the problems of capturing more and better data about the fundamental nature of simulation development and use and they suggest the means to begin spreading our current knowledge, both fundamental and otherwise, throughout the practitioner community.

Interestingly, the participants did not naturally recommend conducting another workshop of this type, an unusual occurrence and, perhaps, a phenomenon of the simulation field itself. This probably results from the focus upon the workshop problems that the participants held throughout its proceedings. Their purpose was, admirably, to solve the workshop sponsors' problems rather than perpetuate seemingly endless discussion of those problems. Every workshop should benefit from such resolve.

During the workshop, Mr. Lunceford, Director of AMSO, observed that simulation technology has been stalled for the last three to five years. The phenomena that we can simulate today are no different than those that we could represent five years ago. We do not move forward because we allow people to cycle through the same ideas over and over again. The current system has no rigor and that hinders our progress in advancing the technology and, thus, its practices. The results of this workshop provide substantive material and realistic recommendations for breaking this technology log jam. Over the long term, scientific knowledge of simulation phenomena may evolve from these recommendations.

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